



Distributed hydrological modelling and application of remote sensing data

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Environment & Resources
Technical University of Denmark



Distributed Hydrological Modelling and Application of Remote Sensing Data

Jens Asger Andersen

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Ph.D.-Thesis
June 2001

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Preface

The present thesis “Distributed hydrological modelling and application of remote sensing data” has been submitted as part of the Ph.D. degree at the Technical University of Denmark. The thesis is organised as a synopsis with three appendixes attached. The synopsis describes, in an overall fashion, the background, the content and the further perspectives in the present work. The appendixes constitute the actual scientific work in the form of three papers. The paper in appendix A is published in Journal of Hydrology, the paper in appendix B is accepted for publication in Hydrological Processes and the paper in appendix C is submitted for publication in Journal of Hydrology. The papers are not included in this www-version but can be obtained from the Library at Environment & Resources DTU, Bygningstorvet, Building 115, Technical University of Denmark, DK-2800 Lyngby (gh@er.dtu.dk).

The present Ph.D. study is part of the INTEO project (INTEgration of Earth Observation data in distributed hydrological models) funded by the Danish Research Councils. The INTEO project constitutes another Ph.D. and a Post doc. working parallel to the present Ph.D. on “Development and validation of methods for estimating key variables in hydrological models of large watersheds using EO-data”. The outcome of the present Ph.D. study is therefore highly a result of the integrated work between these three studies.

The study was carried out from August 1997 to March 2001 at Environment & Resources (E&R), Technical University of Denmark (DTU), under supervision of Professor Karsten Høgh Jensen (E&R) and Professor Jens Christian Refsgaard, Department of Hydrology, Geological Survey of Denmark and Greenland (GEUS). I gratefully acknowledge both for their inspiration, competent guidance and never failing support. More than one year of the study was spent at the Hydrological Modelling Department at DHI Water & Environment being a participating institution in the INTEO project. In addition four months were spent at the Hydrology and Water Resources (HWR) Department, University of Arizona, with Hoshin V. Gupta as the formal supervisor. I would like to thank all formally and informally involved persons from E&R, DHI and HWR as well as from the INTEO participating institutions (Institute of Geography, University of Copenhagen and Centre de Suivi Ecologique, Dakar, Senegal). A special thank to the close colleagues from INTEO; Gorm Dybkjaer, Inge Sandholt, Kjeld Rasmussen and Eggert Hansen.

Lyngby, March 2001,

Jens Asger Andersen

Abstract

The use of physically-based distributed hydrological models demands comprehensive amounts of data both to parameterise and force the model as well as to validate it. Conventionally measured data are mainly restricted to point measurements which are less optimal for use in a spatial distributed context. However, remote sensing can offer such area integrated measures albeit through a more indirect measure than in conventional measures.

In the present thesis a modified version of the physically-based distributed MIKE SHE model code has been applied to the Senegal River Basin using conventional and remotely sensed data, respectively. The first study (reported in appendix A) investigates the model performances to be obtained using only conventional data. A rigorous procedure is applied in the parameterisation, calibration and validation of the model in order to maintain control of the data use and enable examination of the effects of calibration and internal model validation. Calibration against one station and internal validation against eight additional stations revealed significant shortcomings for some of the tributaries, in particular in the semi-arid zone of the river basin. Further calibration against additional discharge stations improved the performance levels of the validation for the different subcatchments. Due to lack of validation data below the subcatchment scale the model could only be validated at this scale.

Remotely sensed estimates of soil moisture seem to be a possible solution to such a validation below subcatchment scale and can also be used to update the soil moisture state variable in the model. The second study (reported in appendix B) investigates the perspectives in using a remotely sensed dryness index in the model. The index is derived from observations of surface temperature and vegetation index as measured by the NOAA-AVHRR sensor. The index is examined for its relation to model simulated soil moisture and evaporation. The correlation results between the index and the simulation results are of mixed quality. A sensitivity analysis, conducted on both estimates, reveals significant noise on both. The study suggests that the remotely sensed dryness index with its current use of NOAA-AVHRR data does not offer information that leads to a better calibration or validation of a simulation model in a spatial sense.

However, the method may potentially become more suitable with the use of the upcoming high temporal MSG data.

The final study (reported in appendix C) investigates the benefit of using remotely sensed precipitation and leaf area index (LAI) as compared to conventional estimates. Precipitation was found to be the most important input data type in the two previous studies and therefore even small improvements of this variable could be of interest. LAI is a less important input variable, however, the methods for estimating this variable from remote sensing are very promising. The introduction of remotely sensed LAI shows improvements in the simulated hydrographs, a marked change in the relative proportions of actual evapotranspiration comprising canopy evaporation, soil evaporation and transpiration, while no clear trend in the spatial pattern could be found. The remotely sensed precipitation resulted in similar model performances on the simulated hydrographs as with the conventional raingauge input. A simple merging of the two inputs did not result in any improvement.

Resume (in danish)

Anvendelsen af fysisk-baserede distribuerede hydrologiske modeller kræver meget store mængder data både til at parameterisere og drive modellen samt til at validere den. Konventionelt målte data udgøres primært af punkt målinger, som er mindre optimale i anvendelser baseret på rumlige distribuerede sammenhænge. Remote sensing kan derimod tilbyde sådanne areal integrerede målinger, selvom der her er tale om mindre direkte målinger af de pågældende variable end ved de konventionelle målemetoder.

I nærværende studie anvendes en modificeret udgave af den fysisk baserede distribuerede MIKE SHE model på Senegal flodens opland med brug af henholdsvis konventionelle data og remote sensing data. Det første studie (rapporteret i appendix A) udforsker hvor god en model der kan opnås ved alene at anvende konventionelle data. Herunder anvendes en streng procedure i parameteriseringen, kalibreringen og valideringen af modellen med henblik på at kunne kontrollere brugen af data og muliggøre en undersøgelse af effekten af kalibrering og af den interne validering af modellen. Kalibrering mod en nedstrøms station og intern validering mod otte opstrøms stationer viste klare svagheder i nogle af deloplandene, specielt i den semi-aride del af flodens opland. Yderligere kalibrering mod flere stationer forbedrede model-kvaliteten i valideringen af deloplandene. På grund af mangel på valideringsdata kunne modellen dog kun blive valideret på en skala svarende til deloplandene.

Estimering af jordvand fra remote sensing data kunne være en mulig løsning på den manglende validering på skalaer mindre end disse deloplande og kunne desuden anvendes til opdatering af jordvands-variablen i modellen. Det andet studie (rapporteret i appendix B) udforsker perspektiverne i anvendelsen af et remote sensing baseret tørhedshedsindex i modellen. Dette tørhedshedsindex er fremkommet fra observationer af overfladetemperatur og vegetationsindex målt af NOAA-AVHRR sensorer. Tørhedsindexet er undersøgt for dets relation til modelsimuleringer af jordvand og fordampning. Korrelationsresultaterne mellem disse er af varierende kvalitet. En følsomhedsanalyse, udført på begge typer af estimater, viser en betydelig støj på begge. Studiet antyder generelt at det anvendte tørhedsindex baseret på NOAA-AVHRR data ikke kan frembringe en information, der kan føre til bedre rumlig kalibrering eller validering

af en simuleringsmodel. Tørhedsindex-metoden kan dog potentielt blive mere anvendelig med brug af nye remote sensing (MSG) data med højere tidslig opløsning.

Det sidste studie (rapporteret i appendix C) udforsker fordelene ved brug nedbør og blad areal index fremkommet fra remote sensing i forhold til konventionelle estimeringer. I de foregående studier fremgik nedbøren som den mest betydningsfulde input data type og derfor burde selv små forbedringer i estimeringen af denne variabel kunne medføre en betydelig forbedring af modellens kvalitet. Blad areal index er en mindre vigtig input variabel, men i dette tilfælde er remote sensing derimod en meget velegnet tilgang til estimering. Anvendelsen af remote sensing estimeret blad areal index i modellen viste forbedringer i de simulerede hydrografer, en klar ændring i de relative proportioner af aktuel fordampning fordelt på canopy fordampning, jord fordampning og transpiration, mens der ikke fremstod nogen klar trend i de rumlige mønstre. Anvendelsen af remote sensing estimeret nedbør medførte en model-kvalitet, med hensyn til de simulerede hydrografer, på niveau med model-kvaliteten fremkommet ved konventionel nedbør. En sammenlægning af de to typer input medførte heller ikke nogen betydelig fremgang i model-kvalitet.

Table of contents

1. Background.....	1
1.1. Study area.....	3
2. Distributed hydrological models.....	4
3. Modelling the Senegal River Basin using conventional data.....	7
4. Applications of Remote Sensing in hydrology.....	12
5. Soil moisture estimates from remote sensing – the TVDI method.....	16
6. Use of remotely sensed LAI in a distributed model.....	20
7. Use of remotely sensed Precipitation in a distributed model.....	26
8. Outlook	28
9. References.....	30

Appendix A

“Andersen, J., Refsgaard, J.C. and Jensen, K.J. (2001a): Distributed hydrological modelling of the Senegal River Basin – Model Construction and Validation. Journal of hydrology, 47, 200-214”

Appendix B

“Andersen, J., Sandholt, I., Jensen, K.H., Refsgaard, J.C. and Gupta, H. (2001b): Perspectives in using a remotely sensed dryness index in distributed hydrological models at river basin scale. Accepted for publication in Hydrological Processes”

Appendix C

“Andersen, J., Dybkjaer, G., Jensen, K.H. and Refsgaard, J.C. (2001c): Use of Remotely Sensed Precipitation and Leaf Area Index in a Distributed Hydrological Model. Submitted to Journal of Hydrology”

1. Background and introduction

The need for and potential of including remotely sensed (RS) data in hydrological models have been identified for some time now. The earliest studies date back to the early and mid seventies (e.g. Ragan and Jackson, 1975), where LANDSAT based land use mapping were used in connection with hydrological models. For some reasons, the utilization of RS data has not become as widespread as expected, in spite of the vast amount of data and different sensors taking advantage of both optical, infrared and microwave spectres that are available today.

Traditional hydrological models are not designed for and not well suited for making use of RS data. This accounts especially for the lumped type of models considering input data and state variables as average values over an entire catchment or subcatchment which typically has an area of several hundreds of km². However, some examples of modified lumped models, successfully using RS data, can be found (Kite and Kouwen, 1992). Distributed hydrological models (DHM) with a regular squared model grid are most well suited for using RS data. DHM's which furthermore have detailed physically-based descriptions of surface processes and state variables appear to have the largest potential for making full use of RS data. However, most classical hydrological models, even the distributed physically-based ones, require some adaptations to fully utilize RS data, because the input data and state variables which can be assessed from the RS data are not all explicitly included in the models. One of the most promising example, of a (semi-) distributed model utilizing RS data, is the SLURP model (Kite, 1995). However, the practical use of RS data in this model has been restricted to snow cover estimation, land cover estimation and LAI evolution (e.g. Kite, 2000) while RS estimation of snow water equivalent is a potential use but associated with less confidence.

A classical example of a physically-based DHM is MIKE SHE (Refsgaard and Storm, 1995), which is a further development of the Systeme Hydrologique Europeen, SHE (Abbott et al., 1986a; b). A DHM, with a much simpler subsurface process description,

which is not based on a squared grid spatial discretisation, but with a comparable description of surface processes, is WATBAL (Knudsen and Refsgaard, 1986). It is computationally much faster than MIKE SHE and as such better suited for application to large river basins. Both MIKE SHE and WATBAL are examples of classical DHM's which are very well suited and only require relatively small adaptations to make full use of RS data. Experience shows that WATBAL and MIKE SHE are equally well suited for simulation of runoff (Refsgaard and Knudsen, 1996).

For optimal use in the present study the two DHM's were merged in such a way that the simple WATBAL process descriptions were integrated as options in MIKE SHE (Christerson, 1997; Andersen et al., 2001). The model was used with conventional data in the study of Andersen et al. (2001) (appendix A) with the overall long term objective of:

- ◆ Constructing a large-scale, distributed hydrological model applicable for coupling to remote sensing data

A general discussion of distributed hydrological models, including a summary of the present results obtained with MIKE SHE, is found in section 2.

The perspectives of integrating RS data into the modified version of MIKE SHE were:

- to improve the simulation of runoff from river basins, in particular in areas with sparse coverage of traditional data.
- to enable internal validation of DHM's, i.e. to check whether the spatial pattern of e.g. soil moisture is reasonably correctly simulated (without RS data, usually only the goodness of the runoff simulation, integrating at least the area of a subcatchment, can be checked). DHM's which have been validated also against measurements of internal state variables have higher reliability when used for prediction of impact of human activities in some parts of the river basin.

- to enable preparations of improved forecast of river flows, irrigation requirements and crop status through updating of state variables in the DHM by assimilation of RS data.

An initial step in the INTEO project was to identify key variables to be estimated from RS data for implementation in the model. As discussed further in section 1.3 the final choice came on soil moisture, LAI and precipitation. The objectives and conclusions on implementing these variables in the modified MIKE SHE are discussed further in section 4-6 and in the papers in appendix B and C, respectively.

1.1 Study area

The Senegal River Basin has been chosen as the case study area. It is one of the major river basins of Africa and encloses four countries (Senegal, Mauritania, Mali and Guinea – see maps on p. 9 and 11 in app. A). The Basin covers diverse environments from arid areas in the north to nearly tropical areas in the south and is only sparsely covered by conventional data collection. The optimal use of sparse water resources is of extreme economic and political importance to these countries, and allocation of water resources is already an important source of international tension – and even conflict – in the area. Establishment of a DHM with RS data input, allows further testing of scenarios with regard to climate change, change in allocation of water for irrigation, dam construction etc., and would be a contribution to improving transnational watershed management procedures. The results of such testing would be directly relevant to a number of other large basins in Africa and elsewhere, such as the Nile, the Niger and the Zambesi-basins, all of which are of extreme importance and sources of international tension.

The methodological focus of the present study has of course a wider perspective as well. Integration of RS data into DHM's will be useful even at smaller scales and in any region, including Denmark.

2. Distributed hydrological modelling

The introduction of physically-based distributed modelling, by Freeze and Harlan in 1969 and later by Abbott et al. in 1986 with the SHE model, seemed to mark a shift towards such physically-based models. Meantime introduction of geographical information systems and increased computer power has favoured the use of such models. At present a great variety of systems are being used regularly for both research and practical applications, ranging from fully physically-based distributed systems such as MIKE SHE (Refsgaard and Storm, 1995) towards semi-distributed conceptual systems such as WATBAL (Knudsen and Refsgaard, 1986) and TOPMODEL (Beven, 1995). One of the main discussions in the last decade on distributed models has been on the value of physically-based versus conceptual process descriptions (e.g. Beven, 1989; 1995, 1996a, 1996b; Grayson et al., 1992; Refsgaard et al., 1996). A major problem with physically-based distributed models is that in practise they tend to function as lumped conceptual models due to lack of data and limitations in computer processing time. While the latter problem will decrease in the future no clear solution on the data problem seems evident. Although the present study on use of remotely sensed data is a step in this direction there are still many processes, e.g. in the unsaturated and saturated zone, that can not be parameterised in a physically-based way by the presently or near-future available data sources.

With regard to the typical application of a hydrological model on simulation of discharges under stationary catchment conditions, several studies have shown that this topic can be addressed equally well by simpler hydrological models such as the lumped conceptual models (e.g. Refsgaard and Knudsen, 1996). As outlined in Refsgaard et al. (1996) this leaves three major problems that in many cases are best addressed by distributed models:

- Simulation of the effect of catchment changes due to human interference, such as land use change, groundwater development, wetland management and irrigation
- Water quality and soil erosion modelling
- Research on hydrological processes

In the present study the modified version of MIKE SHE has been used for research on hydrological processes but as mentioned in section 1 the model has many potential subsequent uses in the present study area.

If all parameters in a distributed model are allowed to vary freely in a calibration process the model is excessively overparameterised (Beven, 1996b) and hence the credibility of the model predictions may be limited. Therefore, it is crucial to adopt a rigorous parameterisation procedure aimed at assessing most of the parameter values directly or indirectly from field data in an objective way and identifying a minimum number of parameters to be adjusted through the calibration process (Refsgaard, 1997).

When the physically-based distributed models were introduced they were most optimistically thought of as being models that could be used without prior calibration, because all model parameters should be identifiable from field data (Abbott et al., 1986a; Bathurst and O'Connell, 1992). As a logical follow up along this line of thought Ewen and Parkin (1996) suggested a "blind" model validation procedure, where no calibration was allowed. In practice, however, partly due to lack of the necessary detailed data or due to a too coarse model grid resolution, it is usually necessary to assess some of the parameters through calibration.

The fundamental question whether a model can be validated at all has been subject to considerable discussion and dispute during the past decade, e.g. by Beven (1989), Konikow and Bredehoeft (1992), De Marsily et al. (1992), Oreskes et al. (1994) and Beven (1996a). However, as mentioned by Hassanizadeh and Carrera (1992) no consensus on methodology (or terminology) exists. In the present study (appendix A) the term validation is therefore carefully defined and the conducted validation tests are designed within the framework of a rigorous test scheme.

A particular problem in relation to validation of distributed hydrological models is that, while spatial data such as topography, soil type and land cover usually are available as

input data, spatial data are seldom available for calibration and validation (Rosso, 1994; Beven 1996a; Refsgaard, 1997). Therefore, distributed models can usually only be calibrated and validated against discharge data, which fundamentally limits the documented performances of such models. In the few examples reported in the literature, where a model has been calibrated against discharge data at the basin outlet and subsequently been subject to validation tests against field data on internal variables, these test results are generally of less accuracy than the results of the validation tests against discharge data, e.g. Ambroise et al. (1995), Refsgaard et al. (1997) and Jayatilaka et al. (1998).

When a distributed model is applied on a regional scale with a coarse data basis, as e.g. the present case with the entire Senegal River Basin, the problem of scale becomes important. Many processes are known to occur at a scale smaller than the computational grid that may be several square kilometres, and there are significant scale differences between the input data and the model grid. Although the model is based on a physically-based distributed code, it inevitably comprises a considerable element of lumping implying that the grid scale simulations are not necessarily representative for the conditions at a scale less than the grid scale.

According to both Refsgaard et al. (1996) and Beven (1996a; b) hydrological science is awaiting the development of new measurement techniques, especially with respect to spatial data and their heterogeneity. Remote sensing seems to be one of the most promising techniques in this context. However, whether the future will generally bring more complex or more simple distributed hydrological models seems to be an open question (Refsgaard et al., 1996; Beven; 1996). According to Entekhabi et al. (1999) “The new information available from remote sensing technology may initiate important shifts in the conceptual basis for hydrology. Analogous shifts have already occurred in the atmospheric and oceanic sciences, where space-based observations have led to the reformulation of many fundamental disciplinary ideas. Hydrologists should be ready to embrace this special

opportunity to rethink prevailing theories and approaches. The benefits for their discipline may be considerable.”

3. Modelling the Senegal River Basin using conventional data

The long term objective of the paper in appendix A, “Distributed Hydrological Modelling of the Senegal River Basin – Model Construction and Validation”, is to construct a large-scale, distributed hydrological model applicable for coupling to remote sensing data. The three major topics addressed in this context are:

- to test the usefulness of conventional data for construction of a distributed model
- to establish a parameterisation, calibration and validation procedure that in a transparent way documents how the existing data are utilised and what the documented model performances are at different spatial scales
- to identify the limitations of the model performance given only conventional data and hence identify the potential for improvements if spatially distributed remote sensing data are introduced.

The following two main principles were adopted in the parameterisation procedure:

- The parameter classes (soil types, vegetation types, climatological zones, etc.) were defined so that the parameter values to the highest extent possible could be identified in an objective way using the available field data and transfer functions. This should ensure transparency and reproducibility of the parameter assessments.
- The number of real calibration parameters was kept as low as possible by fixing the relative spatial pattern of a parameter while allowing the absolute level to be modified by calibration. This facilitates the calibration process and makes it more robust, and it may be argued that it ensures a higher degree of credibility to the subsequent model predictions as the model is not overparameterised.

An important benefit of this approach is that it is easier to distinguish between field-assessed parameters and the parameters that have been fitted through calibration. The number of free parameters were thus limited to four at the maximum per subcatchment, which is comparable to or maybe even less than the number of parameter values that typically are subject to calibration in traditional conceptual hydrological models.

The data available for model calibration and validation were discharge time series from nine stations covering the upper 250,000 km² of the basin. To examine the effects of calibration and to enable internal model validation tests three models characterised by different levels of calibration, were constructed:

- 1) An *uncalibrated model* based on estimates from field data, literature and previous studies.
- 2) The uncalibrated model was then calibrated by adjusting four parameters that were assumed constant over the entire river basin. The calibration was carried out against discharge from one downstream gauging station during a five years period resulting in a *one-site calibrated model*.
- 3) The one-site calibrated model was further calibrated by adjusting two of the four parameters for each individual subcatchment resulting in a *multi-site calibrated model*.

The applied conventional distributed data sets were either extracted from the Internet, from FAO's digital soil map or created on the basis of other data using GIS facilities. Time series of precipitation, potential evapotranspiration and discharge were collected from the national meteorological institutions and a transnational river authority, respectively. The simulation results are summarised in Figure 1.

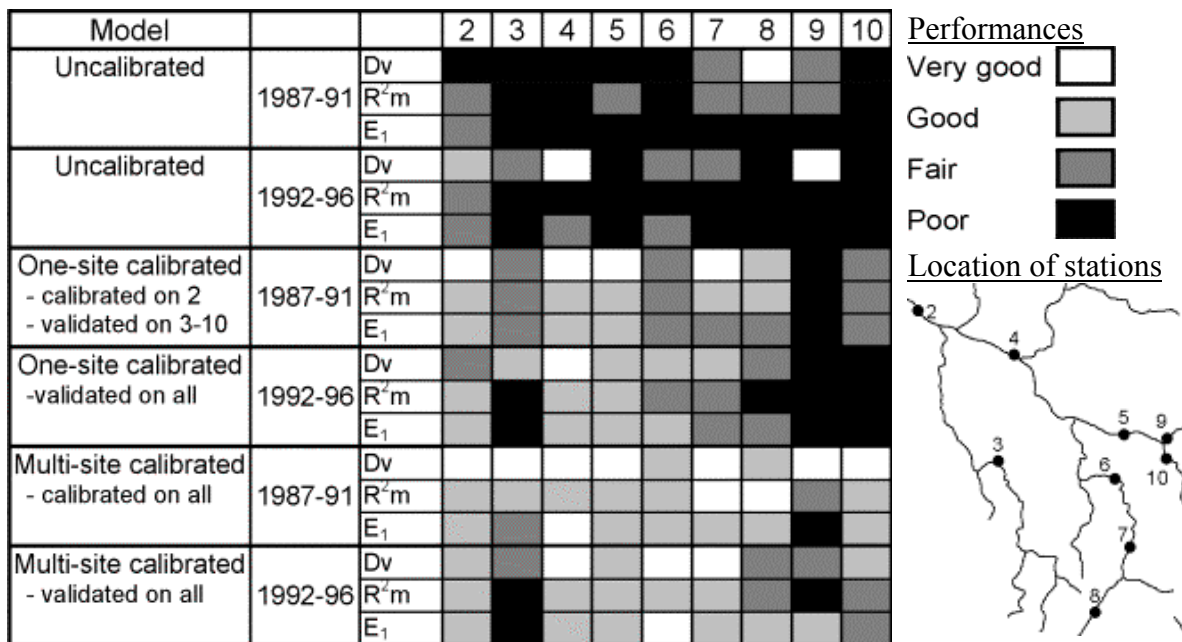


Figure 1. Model performances in the nine subcatchments with the three models, separated in two periods. The three numerical performance criteria's are explained in appendix A

The uncalibrated model, based on standard estimates of the unmeasured parameters, gave a fair to poor performance. The two steps of calibration, based on two previous steps of validation, improved the model performances considerably. The final validation of the multi-site model nevertheless shows that this improvement in model performance does not lead to a real improvement of the model description for all areas. The stations representing the middle area (station 3, 9 and 10) have according to this final validation in general not improved. On the other hand, the discharge stations dominated by outflow from the humid areas maintain the good performances obtained in the calibrations. The final model performance at the subcatchment level therefore falls into two groups: fair to poor performances in the middle zone subcatchments and good to very good performances in the humid source area subcatchments. The performances of the downstream stations (2, 4 and 5) should in principle be a mixture of the upstream station performances but in general their performances are above the average of their upstream stations due to equalisation of the discrepancies.

The internal validation of the one-site model showed worse performances for all stations (3-10) than the calibrated station (2). This is in accordance with the results of Refsgaard (1997) and Jayatilaka et al. (1998).

From the study in appendix A it can be concluded that the multi-scale calibrated model has been validated by the final split-sample test when based on the performance levels documented in Figure 1 (Multi-site calibrated model, 1992-96). However, it must be emphasised that the validation has been carried out at the river basin and at the subcatchment scales respectively and not at scales below these. Thus, although there may be good reasons to believe that the simulation results also to a large extent reflect field conditions at a smaller scale, this could not be tested due to lack of data, and hence no claims can be made on validation status at smaller scales. Similarly, the ability of the models to simulate other variables than discharge could not be tested due to lack of relevant data.

The tendency that the model performances for the three middle zone stations are significantly lower than those of the other stations can not be explained entirely by measurement errors in the hydrometeorological data. The main contributing factor is more likely related either to an inappropriate description of subgrid processes and/or to a too coarse resolution of the input data. The present attempt on simulating the hydrological processes for a large river basin by a model requires major assumptions and simplifications both with respect to the description of the individual processes and the data basis.

A scale related limitation is the model discretization into grid sizes of 4 km x 4 km. Many subgrid processes such as local redistribution of surface water due to spatial variability in topography, vegetation cover, crust development and macropores are not described properly using this discretization. Results from the similar HAPEX-Sahel area points out the “importance on parameterising these subgrid runoff processes to arrive at a meaningful water balance on larger scales such as a GCM gridbox” (Dolman et al., 1997). In the work by Flitcroft et al. (1991), on the same area, the redistribution of surface water is also found

to be a dominating process and they find it difficult to estimate areal averages of the water balance processes. At the field scale the water is essentially redistributed from the non-vegetated crusted areas to vegetated non-crusted areas (Bromley et al., 1997; Peugeot et al., 1997). At larger scales (1-10 km²) the surface water ends up in pools where it either evaporates or infiltrates (Desconnets et al., 1997). Because the distance between the river branches is generally much larger than the distance between the pools, the infiltrated water in the pools can either reach the river as fast interflow or more slowly as baseflow. Since the water balances for the pools are highly dominated by local effects these should be taken into account on the catchment scale because of the non-linearities involved (Dolman et al., 1997; Peugeot et al., 1997). Using a 4 km x 4 km grid size in the present model implies that these effects are not explicitly taken into account.

Another significant limitation in the present study is the data availability. Particularly the soil information is poor both with respect to the classification of soil types and the related soil characteristics and soil depths. Also the point measurements of the prevailing convective precipitation are uncertain as shown previously by Lebel and Barbe (1997) for the HAPEX-Sahel area.

Hence, the constructed models can not be expected to provide a credible simulation of the processes at the grid scale, and the examined simulations of discharge at subcatchment and even river basin scales are certainly also affected by the above limitations.

In the dry northern part of the basin (< 400 mm rain/year) some local redistribution of water probably takes place, but since nearly no runoff is generated, the overall water balance should be simulated with acceptable accuracy. In the middle zone (400 to 1000 mm/year) some of the small scale redistribution processes found in the HAPEX-Sahel study most certainly take place making it more difficult to obtain an accurate simulation of the water balance for this region. For the southern wet part of the basin (> 1000 mm/year) the drainage network is connected down to a relatively small scale, and much less redistribution of surface water will take place compared to the middle zone. An

unpublished sensitivity study also showed the soil and vegetation parameters in this region to be less sensitive since the soil water storages are full about one month into the rain season and from hereof the flow is mainly determined by the climatic conditions. Consequently it is comparably easier to obtain more reliable simulation results for this region.

In order to model the subgrid processes, a much finer resolution of many data types would be needed and a significant increase in computational load would result. Giving the present possibilities this appears unrealistic for the size of the investigated river basin. Improving the resolution of the input data seems more realistic and the combination of finer spatial resolutions and introduction of new data types in the model may lead to future improvements.

4. Remote sensing in hydrological modelling

Remote sensing (RS) is simply defined as the observation of a target by a sensor without physical contact. Data collection with RS can be done with sensors on the ground (hand-held, truck-mounted, etc.) and on a variety of airborne and spaceborne platforms. The sensors used for hydrological applications cover a broad range of the electromagnetic spectrum, including reflective, thermal and dielectric properties of the Earth's surface (Rango and Shalaby, 1999). Both active sensors that send a pulse and measure the return pulse and passive sensors that measure emissions or reflectance from natural sources are used in this context. However, the RS measures are only indirect measures of hydrological variables, so the electromagnetic variables measured by RS must subsequently be related to the hydrological variables using data retrieval algorithms of varying degree of complexity ranging from simple correlation to comprehensive data assimilation schemes. The TVDI-method described in appendix B and the derivation of remotely sensed leaf area index and precipitation described in appendix C are all examples of relatively simple retrieval algorithms based on empirical relations.

The merits of using remote sensing data in distributed hydrological models have been demonstrated in many research studies and are summarised for precipitation by e.g. Petty and Krajewski (1996), snow characteristics by e.g. Rango (1996), evapotranspiration by e.g. Kustas and Norman (1996), soil moisture by e.g. Jackson et al. (1996) and hydrological modelling in general by e.g. Kite and Pietroniro (1996).

Potentially remote sensing can provide information on most hydrological variables, even those placed below the land surface in the unsaturated and saturated zone of the hydrological cycle. However, in practise only the areas of precipitation, snow characteristics, topography and vegetation characteristics have been measured at operational levels (Rango and Shalaby, 1999). Some of the parameters for calculation of evapotranspiration can be estimated from remote sensing but the most important ones such as near-surface temperature and water vapour gradients can not be estimated (Rango and Shalaby, 1999). With respect to soil moisture many attempts have been examined but so far no operational applications based on satellite systems have been developed.

As mentioned in the introduction the focus in the present study is on soil moisture, precipitation and leaf area index and further discussion of remotely sensed estimation of these variables is presented in section 5, 6 and 7, respectively.

The advantage of remote sensing data over conventional data for use in distributed hydrological models increases with the scale of the study area, and is particularly attractive in parts of the world where conventional data are scarce. The present Senegal River Basin is sparsely covered by conventional data and as the basin transverses four countries, the records are rather inhomogeneous. These circumstances make the use of remote sensing data for hydrological modelling attractive, both as input and for calibration and validation.

The general circumstances that make remote sensing techniques attractive in contrast to conventional methods of data collection may be summarised as (from De Troch et al., 1996 and Engman and Schultz, 2000):

- direct digital registration
- areally distributed measurements instead of point measurement (the areal integration is interesting in relation to the scale issue)
- rather high resolution in space and/or time
- no interference between data acquisition devices and the process being measured
- information possible about remote inaccessible areas
- potential to measure system state variables (surface temperature, soil moisture, snow water content, etc.)
- new data forms can be provided (e.g. by combining remote sensing data with other data in a data assimilation scheme or in a GIS or by using the remotely sensed signal directly as a hydrological parameter)

Despite the above advantages of remote sensing only very few success stories on applications of remote sensing in hydrology exist and as mentioned by Kite and Pietroniro (1996) “many studies have suggested that remotely sensed data should provide major benefits to hydrology and water resources and yet there are few case studies that show practical benefits”. The recent WMO report of Rango and Shalaby (1999) on “Current operational applications of remote sensing in hydrology” discusses the many aspects for this lack of operational uses. They point out the technical, economic and administrative obstacles to overcome to make the optimal use of RS data. But the report also reconfirms the previous statement given by Kite and Pietroniro (1996) and shows that, in defiance of the new technical advances (e.g. new satellite sensors) and scientific contributions, the progress in operational applications is still low.

According to both Rango and Shalaby (1999) and Entekhabi et al. (1999) the new avenue for successful remote sensing applications in hydrology requires an end-to-end optimisation. The first step in this process is to define and demonstrate an objective which

could benefit from RS data. The scientific hydrological community, represented by a “Hydrology and Global Water Cycle” panel, recently defined a priority list of such objectives to NASA at the Easton Workshop in 1998 (www.earth.nasa.gov/visions/Easton/appendix5.html) with precipitation and soil moisture estimation as the top priorities. The next step in the process will be for NASA to examine a possible mission design, including choice of sensors and analysis of maximum spatial and temporal output of the product. Testing of various sensors on the ground or in aeroplanes with various retrieval algorithms in various environments and models constitutes a part of this process. The last step of the process is an estimation of mission costs versus the scientific and societal benefits (Entekhabi et al., 1999).

The use of data retrieval algorithms can be found in both RS and in-situ data applications in hydrological models. However, the dependency of such data retrieval algorithms is much more pronounced with regard to RS data.

The most advanced and comprehensive type of data retrieval algorithms are called data assimilation systems (DAS). They are well suited to the distributed physically-based type of hydrological models based on physical principles. The DAS enables control of the conservation of mass and energy, control of the error propagation from the input to the output as well as extension of measurements in time and space. In these ways the DAS works as a “judge system” judging the added value to a system from input of various input data sets. Houser et al. (1998) used the DAS principle to examine the possibilities in horizontal extensions of passive microwave radiance measurements of soil moisture. Calvet et al. (1998) and several others have used the DAS principle to extend the same type of soil moisture estimates, representing only the top few centimetres of the column, to represent the full root zone. Other examples on use of DAS are merging of soil texture measurement and in situ land use data with remote sensing measurements and merging of rain gauge data, ground radar data and satellite based measurement of precipitation.

The remotely sensed estimates used in the present study have all been retrieved by relatively simple empirical retrieval algorithms. However, there can be no doubt that most future retrieval algorithms will be based on DAS. A present example of an operational comprehensive DAS is the Land Data Assimilation System (<http://ldas.gsfc.nasa.gov/>).

5. Soil moisture estimates from remote sensing – the TVDI method

Soil moisture content is an important variable in both hydrological, meteorologic and climatic modelling but is also highly variable in both time and space which makes it very difficult to characterize. Improving the predictive capability of these models requires consideration to this variability (Gao et al., 1996) and much effort has been dedicated to this in the past years (e.g. Houser et al., 1998; Hu et al., 1999). Discussion papers on the future progress in surface water hydrology and climate change studies (Dirmeyer et al., 1999; Entekhabi et al., 1999) also point at a high dedication to this issue. However, a large part of the progress in recent years has been driven by the environmental concern of the future climate which has initiated research in improving mainly meteorologic and climate forecasting (e.g. Hu et al., 1999; GEWEX, 2001) and due to the large scale nature of meteorological and climatological models this research is of most interest in relation to large scale distributed hydrological models that include an energy balance exchange with the atmospheric boundary layer, e.g. through a SVAT (Entekhabi, 1999).

Remote sensing data can serve as a major source in providing spatial data for large scale distributed models, but while remotely sensed estimates of rainfall, vegetation, snow cover, inundated land and wetland areas can be provided at reasonable accuracy for regional scale hydrological models (Dirmeyer et al., 1999; Hsu et al., 1999, Tsintikidis et al., 1999) estimation of soil moisture at similar accuracy has not yet been successful (Dirmeyer et al., 1999). Jackson et al. (1996) state “that there are no satellite systems in operation that are truly capable of reliable soil moisture measurement” and much of the present ongoing

research in the field is therefore dedicated towards finding better sensors for such a satellite (Jackson and Levine, 1996; Famigliette et al., 1999).

Most focus and emphasis in the last years have been on active and passive microwave methods (Jackson et al., 1996; Lakshmi et al., 1997; Dubois et al., 1995) and two missions have even been proposed based on the latter method (Engman and Schultz, 2000).

The active methods, especially the synoptic aperture radar (SAR), can provide extremely good ground resolution from space (> 100 m) (Jackson et al., 1996). However, the temporal resolution with the current satellites is less appropriate (~ 30 days) and distortions from surface roughness and vegetation in general limit the potential operational applications of the method to bare soil surfaces (Hoeben and Troch, 2000). Further research on use of multiple- polarisations, frequencies, incident angles and temporal resolutions may lead to progress (Dobson and Ulaby, 1996; Verhoest et al., 1998).

The passive methods have mainly been tested from the ground or from aeroplanes since there is no satellite in operation with appropriate sensors for these methods. The potential ground resolution from space to be obtained with such a satellite will be very coarse (> 10 km). However, the temporal resolution in such potential measures would be 2-3 days and the distortions from surface roughness and vegetation are much easier to overcome with these methods. The results in Oldak et al. (2001), including soil and vegetation information in the retrieval of soil moisture from passive microwave sensors, are very promising in this context.

One of the major problems that is still unsolved is how to extend the remotely sensed surface signal (representing at maximum the top 5 cm) to be representative for the full root zone, although recent results in this field obtained by Calvet et al. (1998), Wigneron et al. (1999) and Hoeben and Troch (2000) are encouraging.

An additional complication in using the remotely sensed soil moisture in hydrological modelling is caused by the fact that both the remotely sensed and the modelled soil moisture are associated with several types of uncertainties which have to be accounted for. Data assimilation methods (as described in section 4) offer a way of combining input data and simulation results and taking into account their uncertainties, e.g. to update the soil moisture status of the model with the remote sensed soil moisture (Houser et al., 1998). In this context field studies by Western et al. (1999) (10 ha) and Famiglietti et al. (1999) (3.8 km²) have provided information on the natural distribution of soil moisture of great importance for the understanding of relations between natural, model estimated and remotely sensed estimates of soil moisture distribution.

Optical satellite data are inexpensive and can be obtained at relatively fine temporal and spatial resolutions which make their use attractive in operational applications. A few studies, such as Otte et al. (1994) and Castelli et al. (1999), utilize optical data for data assimilation by updating the soil moisture status using remotely sensed surface temperature. However, these methods demand a comprehensive amount of input of meteorological data, which are normally not available in e.g. developing countries and on large scales, and this makes these methods less attractive in operational applications. The empirical methods use a parameterization of the relationship between surface temperature and vegetation index to derive various types of hydrological information such as air temperature (Boegh et al., 1998), evapotranspiration (Carlson et al, 1995) and soil moisture (Moran et al., 1994; Gillies et al., 1997).

In the present study (appendix B) a simple method is applied by which NOAA AVHRR estimates of surface temperature and NDVI are used to derive a Temperature Vegetation Dryness Index (TVDI) (Sandholt et al., 2001). The method is a simplification of the approach described by Moran et al. (1994). The main advantage of the method is that it is valid for vegetated as well as for bare surfaces and only relies on remotely sensed information. In Andersen et al. (1998) it was demonstrated that TVDI correlates well with distributed model simulations of surface soil moisture from 19 points evenly distributed in

the Senegal River Basin and in Andersen et al. (2000b) a qualitative comparison of TVDI and average root zone soil moisture, from two subsequent days, showed similar patterns. A quantitative comparison was done in Sandholt et al. (2001) also showing encouraging results. In this study (appendix B) a more comprehensive quantitative and qualitative comparison of TVDI and model simulations is made to test the usefulness of TVDI for calibration and validation of hydrological models in a spatial sense.

TVDI is examined for its relation to simulated soil moisture and evaporation for a six day period in the wet season 1990. Generally the correlations are low but the correlations between TVDI and root zone soil moisture turned out to be statistically significant in half of the cases. Noise on both the model estimates and the TVDI estimates seems to be the main reason for the non-significant relations. Ideally, TVDI would be very useful support to distributed hydrological models in terms of providing valuable information on spatial soil moisture pattern. However, the TVDI method in its present form based on NOAA AVHRR data, is not sufficiently robust for operational hydrological applications in the Senegal River Basin. The main problem in application of TVDI-estimates seems to be cloud-cover, and effective cloud screening of the AVHRR data turned out to be cumbersome.

The TVDI method, only relying on remotely sensed information, was chosen due to its large operational potential. This study suggests that in order to become operational the accuracy of the TVDI estimates needs to be improved by reducing the influence of noise. This may be achieved by the use of a image data set having a high temporal resolution enabling noise correction of a more slowly changing output variable, in this case soil moisture. The new generation METEOSAT from ESA (MSG) (<http://www.eumetsat.de/>) appears to be able to fulfil this. It has the same spectral bands as the present NOAA AVHRR, nearly the same spatial resolution (~ 2 km) but a much higher temporal resolution of 15 minutes.

As an alternative to this promising improvement of the TVDI method, some of the other methods mentioned earlier could be modified towards more operational methods. The spectral and physically based method of Castelli et al. (1999) showed very promising results using the comprehensive FIFE data set (Betts and Ball, 1998) that includes a huge amount of climatological data. Further testing and modification of this approach, to other more data sparse areas, could be an interesting step towards finding a robust operational method. The active and passive microwave methods still seem to await a technological breakthrough or massive economic investments in order to become operational. Current satellite proposals from both ESA and NASA (Engman and Schultz, 2000) hold some hope in this context, with perspectives of passive microwave estimates of soil moisture of 50 km and 30 km resolutions respectively, with a three day repetition time. Despite the coarse spatial resolution of these prospective estimates they do have operational uses in hydrological models, e.g. in models like the present one on the Senegal River Basin.

6. Use of remotely sensed Precipitation in a distributed model

One of the few areas in hydrology where remote sensing has actually been used in practice is on precipitation estimation. Since precipitation can be considered as the single most important variable in hydrological modelling, at least in surface water modelling, even small improvements have an interest here. This is probably a major reason for the success in using RS precipitation.

The areal distribution of conventional precipitation data, in this case defined as the available meteorological raingauge point measurements, is typically represented through Thiessen polygons (nearest neighbour interpolation) in the distributed models (e.g. Andersen et al., 2001). This simple method has been criticised in several papers (e.g. Suguwara, 1992; Dirks et al., 1998; Haberlandt and Kite, 1998; Ball and Luk, 1998) as a non-optimal method compared to more complicated interpolation methods such as kriging, spline and trend. Other studies (e.g. Seo, 1998; Lebel et al, 1998) have focused on use of

more advanced statistical methods to improve both the temporal and spatial representation. The benefit of the more advanced methods may tend to be mostly academic in the typical application where a daily interpolation is required as input to a hydrological model. A sparse network and high temporal and spatial variability of the rainfall pattern will increase this tendency, e.g. Lebel et al. (1997), who found no correlation between stations exceeding 30 km in distance in the HAPEX Sahel area.

However, with the upcoming of new alternative area integrated precipitation estimates from satellites, ground based radar and atmospheric models (e.g. general circulation models (GCM) and numerical weather prediction models (NWP)), new methodologies need to be developed, in order to integrate all available sources of rainfall information in an optimal way. Obviously, none of the new area integrated methods can approximate the accuracy of the point measurement, when only the point itself or its near surroundings are considered, but as input for a spatially distributed hydrological model, and especially in areas with sparse coverage of conventional stations and a high spatial and temporal variability of the rainfall pattern (e.g. the Sahel), the area integrated methods seem to have a great potential.

The ground radar method can yield a relatively high spatial resolution (e.g. 4 km in the NEXRAD network covering USA) and is very convenient in flood forecasting applications where merged inputs of radar estimates and point measurement have been used with success (Sun et al., 2000; Mimikou and Baltas, 1996). However, due to problems in calibrating the radar signal into exact quantitative precipitation rates the method is not yet at a stage for fully operational use in distributed hydrological models (Georgakakos, 2000). As ground radars are not commonly available in many developing countries other methods must be looked for in such places.

The estimates from GCM has a much coarser resolution than the ground radar (e.g. 400 km in Kite and Haberlandt, 1999) and only seem to have an interest on the macro scale and in areas with a high scarcity of rain gauges. Haberlandt and Kite (1998) found a minor

improvement of the hydrological simulations, on the Mackenzie Basin in Canada, by merging estimates from atmospheric models and measured rain gauge data. Kite and Haberlandt (1999), on a similar study in the same area, found a minor improvement, in some cases, using rainfall data from a NWP model (~50 km resolution) compared to rain gauge data. Yu et al. (1999) also found occasional minor improvements with a NWP model on the Susquehanna River Basin in USA.

A few studies, all from developing countries, have reported on the use of satellite based precipitation in hydrological models. In all cases the measured point data have been used to calibrate the satellite signals and the satellite estimates are therefore optimised towards the measured point data. No merging of the measured point data and the satellite estimates has been attempted and while the temporal resolution varies from monthly to daily values all studies perform a spatial aggregation to either subcatchment or catchment scales.

Two subcatchments from the Senegal River Basin were used by Hardy et al. (1989) as case study areas. Daily satellite derived rainfall (METEOSAT data, using the cold cloud duration technique) were used as input to daily flow predictions using a conceptual rainfall-runoff model (Pitman, 1976). The model “performed at least as well when satellite-based precipitation estimates were used as input in place of conventional precipitation data”. In a study in West-Africa using a simple monthly rainfall-runoff model Pietroniro et al. (1989) found a minor improvement in monthly runoff statistics by use of remotely sensed rainfall compared to conventional precipitation input. Papadakis et al. (1993) did the same comparison for Tano river in West-Africa using a non-linear Volterra series model (Napiorkowski, 1986) and they found that the model simulations of monthly runoff compared equally well to the observations using either METEOSAT based rainfall input or conventional precipitation data. Tsintikidis et al. (1999) reported a similar analysis for the Nile River Basin. They use a conceptual semi-distributed model with a $1 \times 1^\circ$ discretisation and a daily time step. In this case a minor improvement was found using the remotely sensed precipitation and they recommended the use of satellite-derived precipitation together with recalibration of hydrologic models using spatially variable parameter values.

Future studies on the Nile River Basin intend to use daily estimates with a spatial resolution of 5x5 km in a distributed physically-based hydrological model (Todd et al, 1999).

The above reported applications of satellite data for precipitation estimation are all based on geostationary spectral data – in these cases from the European METEOSAT satellite. Data from the similar American GOES satellite are also used operationally to estimate precipitation (e.g. <http://www2.hwr.arizona.edu/persiann/goes.html>). In the study by Kite (1991) spectral data from an orbiting satellite (NOAA AVHRR) were used. However, these estimates did not result in improvements of precipitation input.

Upcoming methods have started to focus on a merging between spectral data from the geostationary satellites and passive and active microwave data from new orbiting satellites such as the SSM/I, “however, efforts to date have not resulted in a product clearly superior to single sensor-based products” (Petty and Krajewski, 1996). The Global Precipitation Mission (GPM) (www.earth.nasa.gov/visions/Easton/appendix5.html) is the newest initiative in this direction, being a follow-up to the Tropical Rainfall Measurement Mission (TRMM) in 1997 (www.trmm.gsfc.nasa.gov), and holds great promises for improvements (Barrett, 2001). The TRMM satellite carries several sensors, including microwave and infrared radiometers and, for the first time, an active radar. The results from this mission are promising (www.trmm.gsfc.nasa.gov), however, the temporal resolution of the output is not at a full operational level. The GPM is intended to lock this gap and launching of eight small satellites connected to a “mother”-satellite, similar to the TRMM satellite, should yield a precipitation output with a temporal resolution of 3 hours and a spatial resolution of 10 km.

According to Rango and Shalaby (1999) the future trend in using rainfall data in hydrological models will be a merging of point measurements, ground radar observations and satellite observations. Actually, the Meteorological Office of UK already uses such an

integration of radar, satellite and rain gauge data with NWP products to generate nowcasts (Golding, 2000).

In the present study (appendix C) the cold cloud duration (CCD) method (Arkin and Meisner, 1987) based on METEOSAT data is used to estimate precipitation for three subcatchments in the Senegal River Basin. In the two other studies on this basin using conventional precipitation input (appendix A, appendix B) precipitation was found to be the most dominant input variable both with respect to the spatial simulations as well as to the integrated discharge simulations. As noted by Pietroniro et al. (1991) the rainfall systems of West-Africa, governed by the inter-tropical convergence zone, are highly suitable for the CCD method.

The applied method is similar to the method of Todd et al. (1999) and is described in Dybkjaer (2001). The precipitation estimates are evaluated using the comprehensive physically-based and distributed MIKE SHE model. Using a distributed model with a daily time step as a test frame will enable a more thorough analysis of the satellite derived precipitation than previous studies by e.g. Hardy et al. (1989), Pietroniro et al. (1989), Papadakis et al. (1993) and Tsintikidis et al. (1999).

The main result in the study (appendix C) is that the model performs equally well with the CCD estimate as with conventional raingauge input. This result is highly in accordance with all the previous similar studies cited above. However, all evaluations are based on case study specific densities of raingauge stations, dominant type of rainfall etc. which makes a direct comparison difficult. In the study of Hardy et al. (1989) they also used the present Subcatchment 1 as their case study area, albeit for another period (1986-87). Their daily coefficient of efficiency, in this specific case, is at the same level as in this study. The present case is the first to include estimates at the grid scale. No specific effect of this has been extracted but it is nevertheless considered as the optimal use of the data.

The two other applications of the model in the area (appendix A and B) point at precipitation as the major input data type in determining both the spatial distribution of hydrological processes as well as the area integrated response. Improved spatial resolution of the precipitation input as in the CCD estimate was seen as an obvious factor to improve the model performance. However, despite some differences in the discharge obtained with the conventional raingauge input and the remotely sensed precipitation input, the overall model performance did not improve and most of the small peaks were still not simulated. The used CCD method is known to rely highly on statistical relations and less on physical ones. Hence, severe uncertainty is attached to the results. However, the spatially distributed output format was expected to improve the model performance by adding information in areas outside the correlation length of the rain gauge stations, as investigated in a scenario with a merged precipitation input from both raingauges and CCD estimates. The lack of a clear improvement in model performance from a scenario with only raingauge input to a scenario with the merged precipitation input implies that the importance of the CCD information is not evident in this context.

However, the spatial input from raingauges and CCD estimates showed considerable differences (> 200 mm/year) in some parts of the area. Hence, considerable differences in hydrographs and model performances could have been expected but presumably due to an aggregation effect of these differences in the downstream direction, the resulting effect at the subcatchment outlet is only moderate on the hydrographs and very little on the model performances. An example from a small upstream area confirmed this theory.

Nevertheless, the study suggest that an improved fit at subcatchment scale, of e.g. the small peaks, seems to depend less on the input data and therefore more on the process equations, the grid scale and the calibration method. New approaches on these areas, e.g. smaller grid size or new process equations, might result in larger benefit of CCD estimates than obtained in the present study.

7. Use of remotely sensed LAI in a distributed model

Estimation of the Normalized Difference Vegetation Index, NDVI, from remote sensing is a well established procedure. Studies by Myneni and Williams (1994), Sellers et al. (1994) and Franklin et al. (1997) suggested that NDVI and leaf area index (LAI) are strongly correlated and LAI is a common input variable for evapotranspiration models (Kristensen and Jensen, 1975; Kite, 1995; Kite, 2000). Since LAI is land cover specific it fits well with models such as MIKE SHE (Refsgaard and Storm, 1995) and SLURP (Kite, 1995) which use land cover information as the basis for parameter definition. An improved representation of the land cover components in these models by introduction of remotely sensed LAI may improve their predictive capability.

The use of remotely sensed LAI in hydrological models and surface schemes has been reported by e.g. Kite (2000) and Habets et al. (1999a) who used NOAA AVHRR satellite data. The present study will specifically investigate the benefit of using remotely sensed (NOAA AVHRR) LAI as compared to standard values.

The evapotranspiration processes are also dependent on the root depths of the plants. Conventionally this parameter is only rarely measured and as a basis for modelling studies it is normally taken from table values or experience from previous studies and for simplification kept at a constant value during the growing season. Schultz (1996) derived root depth from a LANDSAT land use classification where each class was allocated a certain root depth which was kept constant in time. This is an example of a simple and indirect approach in using remote sensing to parameterise the root depths in a model.

In the present study (appendix C) a more dynamic approach is examined. A distinction is made between annual and perennial vegetation types. The perennial vegetation types (such as forest) are given a constant root depth while the annual vegetation types (such as crops and some grass types) vary according to the variation in the remotely estimated LAI.

The results show considerable improvements of the discharge simulations using remotely sensed LAI as compared to conventional predefined LAI. The major reason for this improvement seems to stem from the year to year variation introduced with the remotely sensed LAI.

The applied method on estimating root depth on annual vegetation types, assuming a similar variation as in the remotely estimated LAI, was not tested separately. Some of the improvement on the discharge simulations can therefore originate from the implementation of this method. However, only 18 % of the simulated area is classified with annual vegetation types making it less favourable to conduct an analysis of the effect in this study. Hence, additional studies in e.g. the northern part of the river basin, with more than 90 % annual vegetation, could be interesting in order to obtain a more clear evaluation of the method.

A large impact of remotely sensed versus conventional predefined LAI on the three fractions of evapotranspiration (canopy evaporation, transpiration and soil evaporation) was found. The remotely sensed LAI was generally much higher than the predefined LAI resulting in increased canopy evaporation and transpiration compensated by a decrease in soil evaporation. Such changes can be of particular importance in irrigation studies where an aim is to reduce the canopy evaporation and soil evaporation and maintain the potential transpiration. Assuming the remotely sensed LAI to be the “true” estimate the present results suggests that more reliable results will be obtained with the use of remotely sensed LAI.

In modelling the combined effects of changing climate and vegetation cover remotely sensed LAI also seems to be valuable. The integration of the ISBA surface scheme and the macroscale MODCOU model (Habets et al., 1999a) has actually been developed and tested (Habets et al., 1999b), with the use of remotely sensed LAI, towards the long term objective of predicting such changes. The present results confirm the advantages of such initiatives.

The present use of NOAA AVHRR data for vegetation monitoring will probably be taken over by e.g. the newly launched SPOT 4 satellite (<http://www.spotimage.fr>) carrying a special vegetation instrument and having the same spatial and temporal resolution as the NOAA AVHRR. The 2nd generation METEOSAT satellite (<http://www.eumetsat.de/>), to be launched in 2002, has similar capacities as the present NOAA AVHRR except for a much higher temporal resolution of 15 minutes. This range of new satellite-sensor systems will inevitably lead to improved estimations of vegetation variables like LAI in the future.

8. Outlook

Hydrology and water resources are becoming a growing issue in the public debate and according to UNESCO (Andras Szöllösi-Nagy, personal communication) and WMO (Obasi, 1999) water will be a main issue in this century and in this context the conflicts between countries that share river basins or aquifers have the potential to start new wars.

Growing populations, increased pollution, possible climate change and a generally increased demand for water from several sectors are among the challenges for the future water resources management. Integrated approaches are demanded bringing together all disciplines and sectors involved. Distributed hydrological models are one of the tools which can be used in this regard, however, requiring that the information from the model can be integrated into some sort of a decision support system.

The present study is an attempt to improve the performance of distributed hydrological models and should be seen in the above context. Increased computer power and new theoretical process formulations based on new measurements from especially remote sensing will inevitably improve the value of distributed hydrological models in the future.

The present study has shown the potential uses and benefits of some of the currently available satellite images. However, many new satellites valuable to hydrology have been launched recently or are to be launched in the near future. Improved estimation of vegetation characteristics, precipitation, soil moisture, inundated areas and snow characteristics seems to be an immediate outcome of this.

The methodological approach in the estimation of hydrological variables from remote sensing in the future will inevitably take place with the use of data assimilation systems as part of the “end-to-end optimization” framework described in section 4. Comprehensive validation data sets will be necessary in this context both to handle the error statistics in data assimilation systems as well as for testing of process descriptions in the hydrological models. Currently the data sets from the HAPEX Sahel experiment in Niger, the Southern Great Plains experiment in Oklahoma and the GEWEX experimental sites constitute examples of such needed data sets.

The hydrological society has so far to a large extent not been involved in the development and launching of satellites but has only used the final product to a minor extent. Although the information from many satellites has been used for hydrological purposes no satellites have so far been launched with hydrological applications as the main objective. The example from the Easton workshop in section 4 (www.earth.nasa.gov/visions/Easton/appendix5.html) shows that the hydrological society is now involved in the full process.

One of the consequences of the “end-to-end optimization” framework is that the main scientific input to the process is in the preliminary stages on development of retrieval algorithms, choice of sensor-type etc. After the launch of the satellite the data could optimally be processed at central institutes and (hopefully) distributed for use in the final hydrological format on the internet. Alternatively local institutions should install satellite receivers for further processing by individual users. Recently the EU-Commission financed the establishment of such receivers for the METEOSAT 2nd generation satellite in all Sub-Saharan countries. A such initiative, among others, raises a large hope for the future in

progressive managing of water resources with the use of distributed hydrological models based on remotely sensed information.

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